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FRICTIONLESS SUSPENSION

by

ELECTRO - MAGNETIC REPULSION

RESEARCH LABORATORY
MOORE SCHOOL OF ELECTRICAL ENGINEERING
UNIVERSITY OF PENNSYLVANIA
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In this investigation, it was desired to demonstrate that by properly directing the forces set up by electromagnetic induction, a mass of appreciable weight could be suspended entirely free of mechanical support or restraint whatsoever.

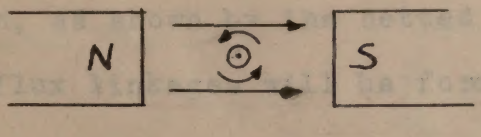
This object was achieved, masses up to 18 ounces in weight being floated.

The repulsion of a secondary winding, free to move in an alternating-current magnetic field, is well-known, having been discovered by Professor Elihu Thompson many years ago. The phenomenon is made of practical use in the constant-current transformer.

Laboratory experiments showing the repulsion of windings are familiar, but up to the present time, it is believed that no one has succeeded in stabilizing a floating inductor over an indefinite, or even appreciable, length of time.

THEORY OF TESTS

When a conductor carrying current is placed in a magnetic field, with the direction of current perpendicular to the flux lines, a sidewise push is exerted on the conductor, as in the following diagram:-



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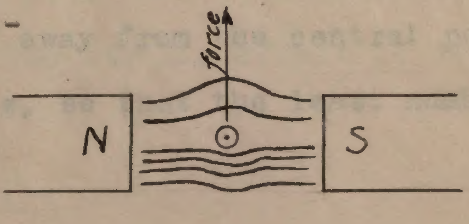

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Current in the conductor is assumed flowing toward the reader, and the horizontal portions of the circular flux paths set up by the current are shown, lessening the field strength above, and increasing it below, the resultant field being as in Figure 2. The magnetic stress seeks the most direct path between poles. If the field is thought to be made up of actual lines of force, each line seeks the path of lowest reluctance. The crowded lines below the conductor tend to straighten and to secure more "elbow room", i.e., a path of greater cross-sectional area for each line. This results in an upward force bearing on the conductor. This force is proportional to field strength and current strength.

If a ring carrying current be placed in an annular magnetic field, represented by the following cross-sectional sketch:

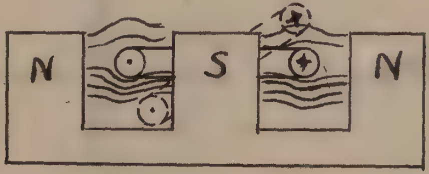


Figure 3

there will be a uniform force bearing upward on the ring throughout its circumference. If this ring could be maintained in the position shown, an ideal frictionless support could be had.

But the ring will slide away from the central position, as shown by the dotted lines, so that the least number of flux linkages will be formed.

We speak of "frictionless support" without stating one requirement--there may be no electrical connection to the

ring. This necessitates generating ring currents by the use of a varying magnetic field. If the field is generated by alternating current, account must be taken of the time-phase relation of field strength and ring current strength.

The field strength will be proportional to and in phase with the exciting current (I_c). The induced voltage in the ring will lag the field strength by 90° $(E = -N \frac{d\phi}{dt})$. Were the ring a pure inductance, its current would lag the induced voltage by 90°. This 180° phase current relation, and the consequent similar flux relation, would result in maximum lifting effect on the ring, thus:-

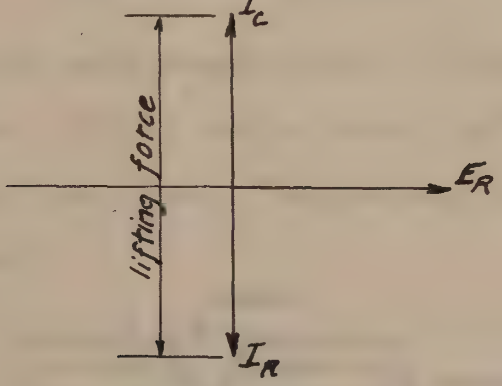


Figure 4

But since the inductive reactance of a solid ring may be only $\frac{1}{4}$ its resistance, the ring current (I_R) lags the ring voltage (E_R) by about 14°. The lifting effect is decreased thus:-

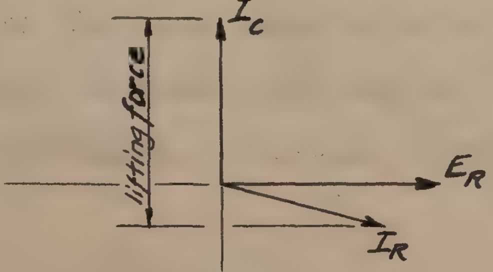


Figure 5

As the vectors rotate, there is a positive lifting force during most of the cycle, and a negative force over a shorter period. The aim is to have the ring reactance as large as possible in proportion to its resistance. A copper ring would be ideal from this standpoint, but even with its higher current, and more favorable phase relation, it is inferior to aluminum due to its much greater weight. The net relative advantage of aluminum to copper is 2/1.

Since a horizontal annular magnetic field will not give stability to a floating inductor, a field must be devised that will supply the necessary centralizing force.

DESCRIPTION OF TESTS

After much experimentation, it was found that a cone-shaped field, with a fairly sharp taper, and a suitably shaped aluminum cone, were required. The device, in cross section, appears as follows:-

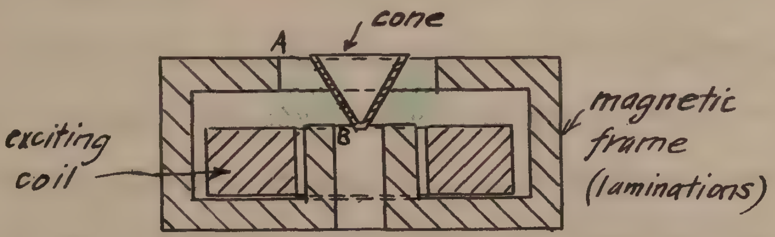


Figure 6

By following the flux lines, it is seen that only the upper portion of the cone receives an appreciable lifting force, while against the lower portion, the force acts mostly as a centralizing influence. In fact, on the bottom of the

cone a downward force is exerted, due to the fringing of flux emanating from the inner pole, near the bottom of the cone. However, when the lowest portion of the cone is removed, say up to $\frac{1}{5}$ its height, it is found that the remainder of the cone is not so easily stabilized. By building out the upper magnetic pole, and, in effect, increasing the slope of the magnetic lines, stability was secured with the shortened cone, thus:-

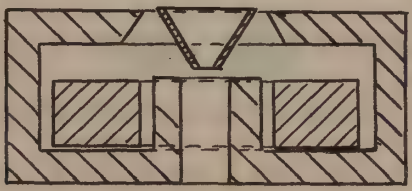


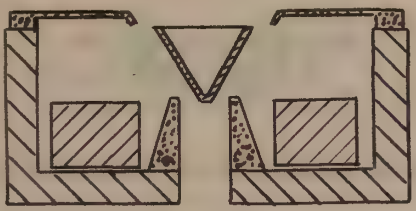
Figure 7

Also by attaching a weight, to lower the center of gravity, stability was secured with this cone.

With the magnetic field as in Figure 6, fed by 60-cycle current, an aluminum cone weighing 0.6 lb. was floated with perfect stability. The full-sized cone floated better in the field, as in Figure 6, than in the one represented by Figure 7. In the latter, the downward force on the lowest portion of the cone is more marked.

The cones float as though immersed in a frictionless fluid, no rotative or auto-rotative forces being evident.

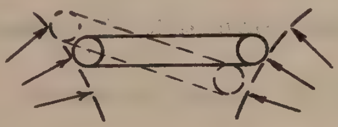
It can be seen that only a fraction of the total flux is utilized. The greatest flux density is between the nearest edges of the poles. It would appear that by cutting away these edges, or by thinning the iron path so that the airgap flux flowed mainly from A to B as in Figure 6, much less flux would be unused. The iron field was redesigned to this effect, as follows:-



The tapering center portion, and the thin upper portion were made of iron filings, held between suitably formed wood molds. This arrangement, instead of showing greater efficiency, showed less, a higher primary current being required than before. This is partly due to the greater reluctance of the iron filings, and partly due to the fact that the bolstering action of the flux flowing between the near edges, as previously, is absent. In other words, when a cone is immersed in this field, the flux seeks to avoid it, and falls away from the cone.

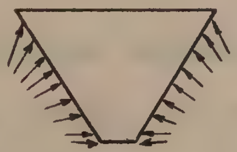
In an effort to secure greater lifting effect from a given field strength, the iron path was reshaped to present a cone of less taper, and an aluminum cone of corresponding taper (50° from the vertical) was used. The lifting force was notably increased, but the cone could not be stabilized.

By employing aluminum rings of $\frac{1}{4}$" thickness, and of varying diameters, the magnetic field, as in Figure 6, was explored to determine the lifting and centralizing forces in different sections. Near the top of the field, there is great lifting force, but a decided decentralizing force is manifested. It can be seen, as in the following, that the ring is sustained as though by frictionless supports in the position shown:-



With the slightest movement away from the horizontal position, the ring is acted upon by forces tending still further to carry it from the original position. It will eventually assume a nearly vertical position where it is cut by the least flux lines.

At the lower part of the airgap, there is very little lifting effort, but a strong centering force is found. Thus the cone is acted upon by forces as follows:-



The centralizing action at the lower portion is required to neutralize the tipping action above. The resultant lifting force is equivalent to a single force acting above the center of gravity of the cone. The small downward force, at the bottom of the cone, aids in stabilizing.

The outstanding difficulty in the practical use of this device as a frictionless support is the heating due to the current in the cone. This can be minimized by grooving the exterior wall circumferentially, and the heat can be dissipated more rapidly by dropping a little water into the cone. As the metal heats, its conductivity is decreased, and a stronger field is required to generate the necessary currents.

The thickness of the cone wall is of little consequence, as far as operation is concerned. With very thin walls, the conductivity may be insufficient for the currents required. Very satisfactory results were had with cones of $\frac{1}{4}$" walls. When two or three similar cones were nested together, the action was excellent, though stronger fields were required.

An aluminum sphere, $4\frac{1}{2}$" outside diameter, and with $\frac{3"}{16}$ wall, floated very well, but since only a comparatively small part of the metal served as an inductor, it was much less efficient than the cone.

Many other aluminum shapes of various patterns were tried in the field. One shaped as an inverted bell to follow the flux lines, was the only other piece to approach stability. Even this shape could not be made perfectly stable.

It was found that with the field as in Figure 6, the distribution of flux was not greatly altered by the insertion of a metal cone. On this basis, and by exploring the field and preparing a plot of the flux lines, calculations were made of the forces acting on each horizontal section, or zone, of the

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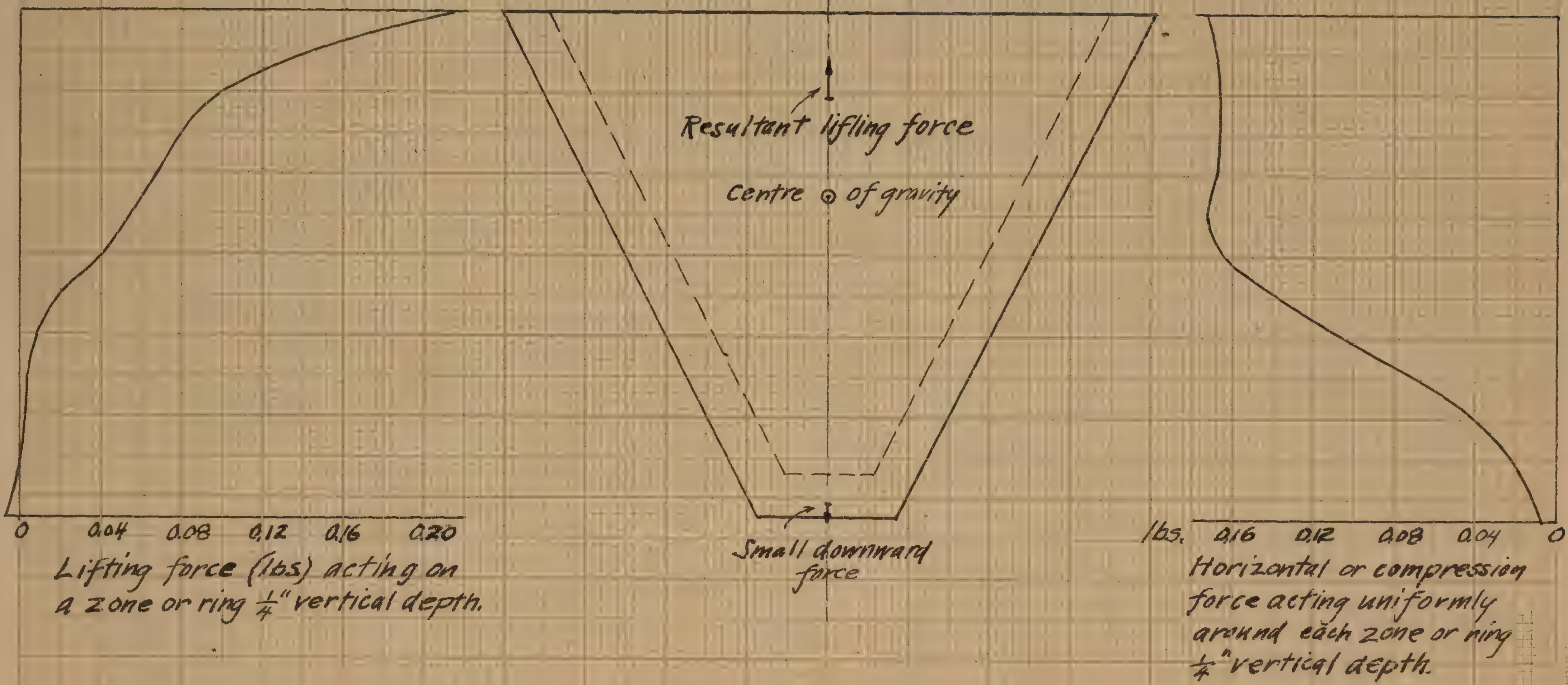
Distribution of Forces on Floating Aluminum Cone.


Resultant lifting force
Centre of gravity
Small downward force
0
0.04
0.08
0.12
0.16
0.20
Lifting force (lbs) acting on a zone or ring ¼" vertical depth.
lbs.
0.16
0.12
0.08
0.04
0
Horizontal or compression force acting uniformly around each zone or ring ¼" vertical depth.

FORM 1-20 24

cone. A graphical representation of the forces is appended.

To construct this plot, the cone was assumed cut by horizontal planes into zones $\frac{1}{4}$" deep; the resistance and inductance of each ring were calculated; the total flux threading each ring was determined from a plot of the magnetic field, and thus the voltage induced in each ring was ascertained; the division of impedance into voltage gave the ring currents, and the product of current and the proper field intensity, taking into consideration flux direction and angle of lag of ring current, gave the force acting on each ring. This force was then resolved into vertical and horizontal components. The sum of the vertical components added to 0.613 lb., which checks quite well with the actual weight of the cone, 0.60 lb.

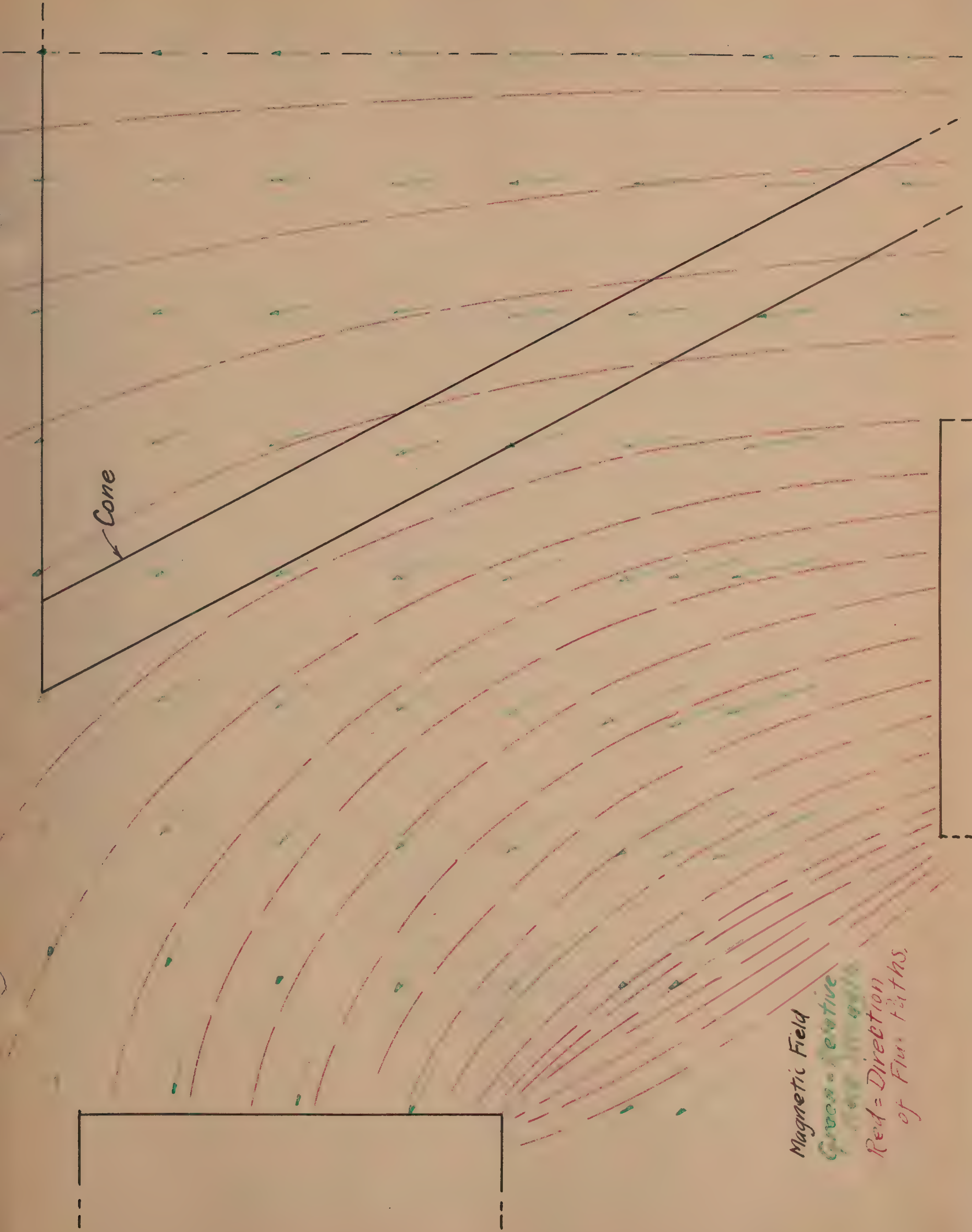
To compensate somewhat for the mutual inductance of the rings, the self-inductances were arbitrarily increased 10%. The resistivity of pure aluminum, 3.03 micro-ohms/cm. cube at 37° C, was used in the calculations. The cones were of cast aluminum, 99+% pure.

Samples and tables of computations are appended.

The field intensity was measured by a small coil of #30 wire, held in a framework that permitted of accurate vertical and horizontal movements. The horizontal and vertical components of field strength were found separately, and combined in the calculations. The coil voltage was measured by a vacuum thermo-couple and a direct-current micro-ammeter. The directions of the flux paths were checked by iron filings

held in a small piece of glass tubing, the filings aligning themselves in the flux paths.

The calculations were made for a flux density corresponding to a primary input of 43 amperes~~,~~ and 240 watts at 64 volts, required to float the cone.


Cone
Magnetic Field
Green = Relative
[illegible]
Red = Direction
of Flux Paths

Calculations for plotting force distribution on floating cone.

D		R	X	Z	Θ	B_m	E	I	F	V	H	α
cm.		(1) ohms·10^{-6}	(2) ohms·10^{-6}	(3) ohms·10^{-6}	(4) deg.	(5) lines/in.^{2}	(6) volts	(7) amps.	(8) lbs.·10^{-3}	(9) lbs.·10^{-3}	(10) lbs.·10^{-3}	deg.
0.312	1	215	61.5	224	16	2820	75.5	337	243	172	172	45
1.12	2	187	48.6	194	14.5	3240	72.1	371	193	96	167	30
2.12	3	165	39.2	170	13.3	3710	63.7	375	180	70	166	23
3.12	4	140	30	144	12	4560	56.8	395	181	50	174	16
4.12	5	114	22.2	117	11	5160	42.2	361	139	22	137	9
5.12	6	90.5	15.7	92.2	9.8	5400	28.0	303	86	6	85	4
6.12	7	67	10.2	68	8.6	5160	14.5	214	38	2	38	3
7.12	8	44.8	6.0	45.2	7.5	3600	7.3	229	15	-0.3	15	-1
	9											
	10											

D = distance (cm.) from top of cone to ℄ of zone where calculations were made.

R = zone resistance.

X = " reactance.

Z = " impedance.

$\theta = \tan^{-1}\frac{X}{R}$

B_m = effective max. flux density over area concerned.

E = Ring or zone voltage.

I = " " " current.

F = " " " force.

V = " " " " vertical component.

H = " " " " horizontal "

α = angle of flux path, from vertical.

Sample Calculations.

Resistance of top zone ($\frac{1}{4}''$ deep) of cone:

$$R = \rho \frac{l}{a} \left(\rho = 3.03 \cdot 10^{-6} \omega/\text{cm}^3 \right) \qquad l = 2\pi \, 4.56\text{cm.}$$

$$a = 0.403\text{cm}^2.$$

$$R = \frac{3.03 \cdot 10^{-6} \cdot 2\pi 4.56}{0.403} = 215 \cdot 10^{-6} \omega.$$

Inductance of top zone of cone:

$$L = 4\pi a \left[\left(1 + \frac{r^2}{8a^2}\right) \ln \frac{8a}{r} + \frac{r^2}{24a^2} - 1.75 \right]$$

(Pender, 2d. ed, p. 824)

$a = 4.56$cm. $r = 0.381$cm. = effective radius.

$$L = r\pi 4.56 \left[(1 + 0.001) \ln 95.6 - 1.75 \right] 10^{-9} = 148 \cdot 10^{-9} \text{ henries.}$$

$$X = 377 \cdot 148 \cdot 10^{-9} = 55.8 \cdot 10^{-6} \omega. \qquad X \cdot 1.10 = 61.5 \cdot 10^{-6} \omega.$$

$$z = \sqrt{R^2 + X^2} = 224 \cdot 10^{-6} \omega. \qquad \theta = \tan^{-1} \frac{X}{R} = 16^\circ.$$

Induced voltage, in ring:

On large plot of field strength, a vector of 1" corresponds to 1.50 milliamps in coil and thermo-couple. Resistance of thermo-couple and coil = 636 + 13 = 649ω.

Voltage generated in coil = (effective exploring coil current over area enclosed by top ring of cone) X (circuit resistance.)

From plot, effective coil current = ~~0.17"~~ 0.212"

Coil voltage = $0.212 \cdot 1.50 \cdot 10^{-3} \cdot 649 = 0.206^{\text{v}}$.

Number of coil turns = 104.

From the equation $E_{eff.} = 4.44\phi_m f 10^{-8} \cdot N$

$$\phi_m = \frac{E_{eff.} 10^8}{4.44 \cdot f.N} = \frac{0.206 \cdot 10^8}{4.44 \cdot 60 \cdot 104} = 753 \text{ lines.}$$

Mean diameter of coil = 0.58 in. Area = 0.264in.^2

$$\therefore \beta_m = \frac{753}{0.264} = 2820 \text{ lines/in.}^2$$

Area enclosed by top of cone = 10in.^2

$$\therefore \text{total } \Phi_m = 28{,}200 \text{ lines.}$$

Ring voltage: $E = 4.44\Phi_m \cdot f \cdot 10^{-8}$

$= 4.44 \cdot 28{,}200 \cdot 60 \cdot 10^{-8} = 0.0755$ v.

Ring current: $I = \frac{E}{Z} = \frac{0.0755}{224 \cdot 10^{-6}} = 337$ amps.

Force acting on ring:

$$F = \frac{\beta l I}{11.3 \cdot 10^6}$$ (Cook, "Elements of Elec. Eng." - p. 48.)

$$\beta = \frac{\beta_m}{\sqrt{2}} \qquad l = 2\pi 1.79 \text{in.}$$

$$F = \frac{2820 \cdot 2\pi 1.79 \cdot 337}{\sqrt{2} \cdot 11.3 \cdot 10^6} = 0.667 \cdot \sin\theta$$

where θ = angle of lag of ring current behind ring voltage

$F = 0.667\ 0.257 = 0.243$ lb.

This force acts on ring perpendicularly to flux direction at mid-section of ring, or 45° from the vertical.

Lifting component of force $= 0.243 \sin 45^{\circ}$

$= 0.172$ lb.

Horizontal component of force $= 0.172$ lb.

Computation oftotal lifting force, from plot:

Zone	lb.	
1 (top)	0.178	
2	0.118	
3	0.088	
4	0.075	
5	0.060	
6	0.047	
7	0.032	
8	0.014	
9	0.005	
10	0.002	
	0.619	
11		0.000
12		-0.002
13	-0.006	-0.004
	0.613	= net lifting force.

Cone weighs 0.60 lb.

A. J. Pyle
July 1926

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